AFFDL TM 74-191-FXN

AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE OHIO

OPERATIONAL TEST OF THE CALSPAN TRANSIENT ENTHALPY PROBE B5M IN AN ARC HEATED REENTRY NOSE TIP TEST FACILITY

November 1974

Approved for public release; distribution unlimited.

TECHNICAL MEMORANDUM AFFDL-TM-74-191-FXN

Experimental Engineering Branch
Flight Mechanics Division
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

This report has been reviewed and cleared for open publication and/or public release by the appropriate Office of Information (OI) in accordance with AFR 190-7 and DODD 5203.9. There is no objection to unlimited distribution of this report to the public at large or by DDC to the National Technical Information Service (NTIS).

This Technical Memorandum has been reviewed and is approved for publication.

William E. Alexander

WILLIAM E. ALEXANDER
Physicist, R&D Group
Experimental Engrg. Br.

FOR THE COMMANDER

for Donald J. Harney

PHILIP P. ANTONATOS
Chief, Flight Mechanics Division
AF Flight Dynamics Laboratory

AFFDL TM 74-191-FXN

OPERATIONAL TEST OF THE CALSPAN TRANSIENT ENTHALPY PROBE B5M IN AN ARC HEATED REENTRY NOSE TIP TEST FACILITY

William E. Alexander

November 1974

Approved for public release; distribution unlimited.

TECHNICAL MEMORANDUM AFFDL-TM-74-191-FXN

Experimental Engineering Branch
Flight Mechanics Division
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio 45433

FOREWARD

Under sponsorship of the Aeronautical Research Laboratory, Wright Patterson Air Force Base, Ohio, Calspan Corporation of Buffalo, New York, developed a large version of their miniature fast acting enthalpy probe as a prototype for measurement in the Air Force Flight Dynamics Laboratory Reentry Nose Tip Test Facility (RENT). Operational tests were performed in RENT during the course of flow calibration tests. Various enthalpy measurement devices were tested at this time. The Calspan probe tests are synopsized in this memorandum.

Under Task Number 142601, "Diagnostic, Instrumentation and Similitude," managed by Mr. Daniel M. Parobek, the tests and this report were carried out and written by William E. Alexander under Work Unit Number 14260122, "Performance Evaluation of the AEDC Probe in Measuring Local Enthalpy in Aerospace Vehicle Reentry Test Facilities".

Preliminary work to the RENT tests was done by Messrs. Arthur Stringer and Kenneth Stout, who were in charge of exploratory tests and RENT installation. Messrs. Hudson Conley and Jon Bader assisted during RENT testing and along with Dr. Edmund Brown-Edwards reviewed the draft of this memorandum. Sgt David Phelps prepared the draft for publication.

The statements in this memorandum are not necessarily indicative of other AFFDL activities. For example, sentence 1 on page 13 does not mean that RENT pressure profiles are normally measured with this probe. In fact, other RENT pressure probes have much higher frequency responses.

ABSTRACT

The Calspan B5M transient enthalpy probe was evaluated in tests at the Air Force Flight Dynamics Laboratory Reentry Nose Tip Test Facility. Its survivability was excellent, melting of components did not occur as it was swept at speeds greater than 50 inches per second across the 1.1 inch diameter flow stream. Its response time was estimated as 2.1 to 3.0 milliseconds. Probe measurements made by use of averaged data were about 20% higher than the facility bulk enthalpy, but the validity of the measurements is questionable because of the sensitivity of the probe to extraneous energy inputs. These are not sufficiently defined to correct probe readings.

TABLE OF CONTENTS

ILLUSTRATIONS

SYMBOLS

H_g. . . . Total Enthalpy of gas at probe aperture

E_T. . . . Voltage across thermal tube

E_p. . . . Voltage output of pressure sensor

G_T. . . . Amplification factor in thermal tube signal conditioning circuit

G_p. . . . Amplification factor in pressure sensor signal conditioning circuit

t. . . . Time

R_T. . . . Resistance of thermal tube

R_L. . . . Lead wire resistance

R_S. . . . Resistor in series with thermal tube

INTRODUCTION

Conventional water cooled enthalpy probes[1,2] cannot survive in high energy supersonic arc heated flows such as the Air Force Flight Dynamics Laboratory ReEntry Nose Tip Test Facility (RENT). However, the technique of sweeping an uncooled probe through extremely high energy, high pressure flows has appeared, since its inception, as a practical approach to measuring enthalpy. One such probe has been developed by Arnold Engineering Development Center[3] and has been tested in RENT[4]. Another probe was developed by Calspan which was designed around predicted RENT enthalpy and pressure levels.

The Calspan probe RENT test results are the primary topic of the memorandum. These are given with reference to the previous design, development, and test work conducted at Calspan[5].

Continuity with the previous Calspan work was maintained by analyzing only the data obtained from test conditions known to be characterized by relatively flat lateral enthalpy profiles.

Drawing straight lines through a linear plot of the data to measure slopes yielded enthalpy values about 20% higher than the values determined by heat balance calculations on the RENT arc heater. A point by point method of analyzing the data was also used and clarified the need for additional signal conditionings and error analysis before automatic online measurements can be obtained over one millisecond intervals. Neither method yielded enthalpy values which can be claimed as accurate indications of RENT enthalpy.

These tests were part of the Flow Calibration Program, RENT test numbers RTN 033-057 to 062, which were conducted over the period 3 to 19 October 1973.

The program also included tests, numbers RTN 033-063 to 072, which were characterized by highly peaked enthalpy profiles. More study of the data is required to evaluate probe performance under these conditions. Therefore, this portion of the program is not covered in this memorandum.

PROBE DESCRIPTION

... proportional to the rate of energy transferred to it from a hot gas flowing within it. The gas is cooled to a low level during its transit through the tube, having entered a small aperture in a covering cap with the same energy content as it possessed in the main flowstream. Pressure in a terminal volume increases at a rate proportional to the mass flow rate of the cooled gas entering it. This is illustrated in Figure 1. Cap and tube survivability is insured by limiting the exposure time sufficiently to prevent melting of these components. The product of a calibration constant and the ratio of the temperature and pressure rise rates is equal to the flow stream enthalpy minus the lowered enthalpy of gas after its transit through the tube. The equation constant and residual gas energy term determined by Calspan are 277,000 BTU-Volts/LBM and 155 BTU/BLM.

The equation of the probe[5], in terms of the transducer outputs is:

$$Hg = \frac{277{,}000}{E_T \times 10^3} \frac{\Delta E_t}{\Delta E_p} + 155 \text{ BTU/LBM} \qquad (1)$$

ΔE_t is obtained from outputs of a half-bridge circuit, and ΔE_t from outputs of the pressure sensor as shown in Figure 2. The half-bridge circuit impedance for the RENT tests was matched as the precision of the available Calspan data would allow. During testing, the outputs of the transducer were amplified and recorded at one millisecond intervals.

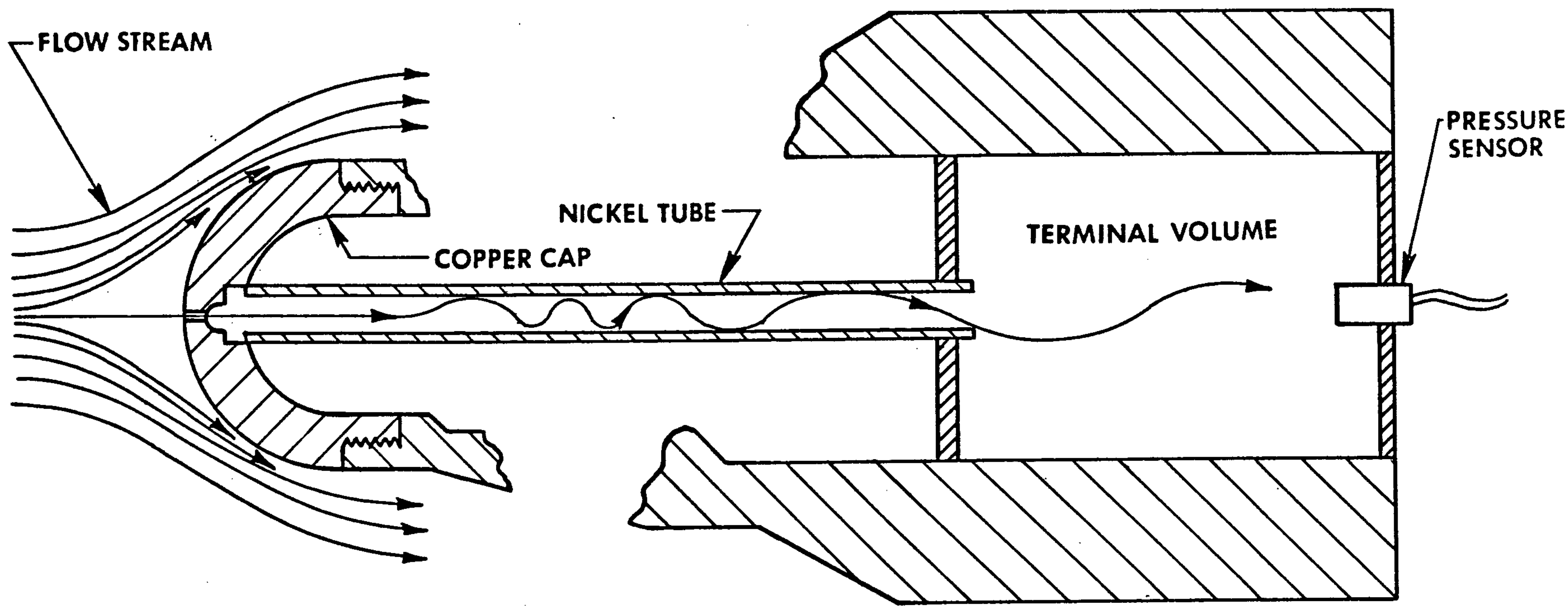

FIGURE 1. MEASUREMENT CONCEPT

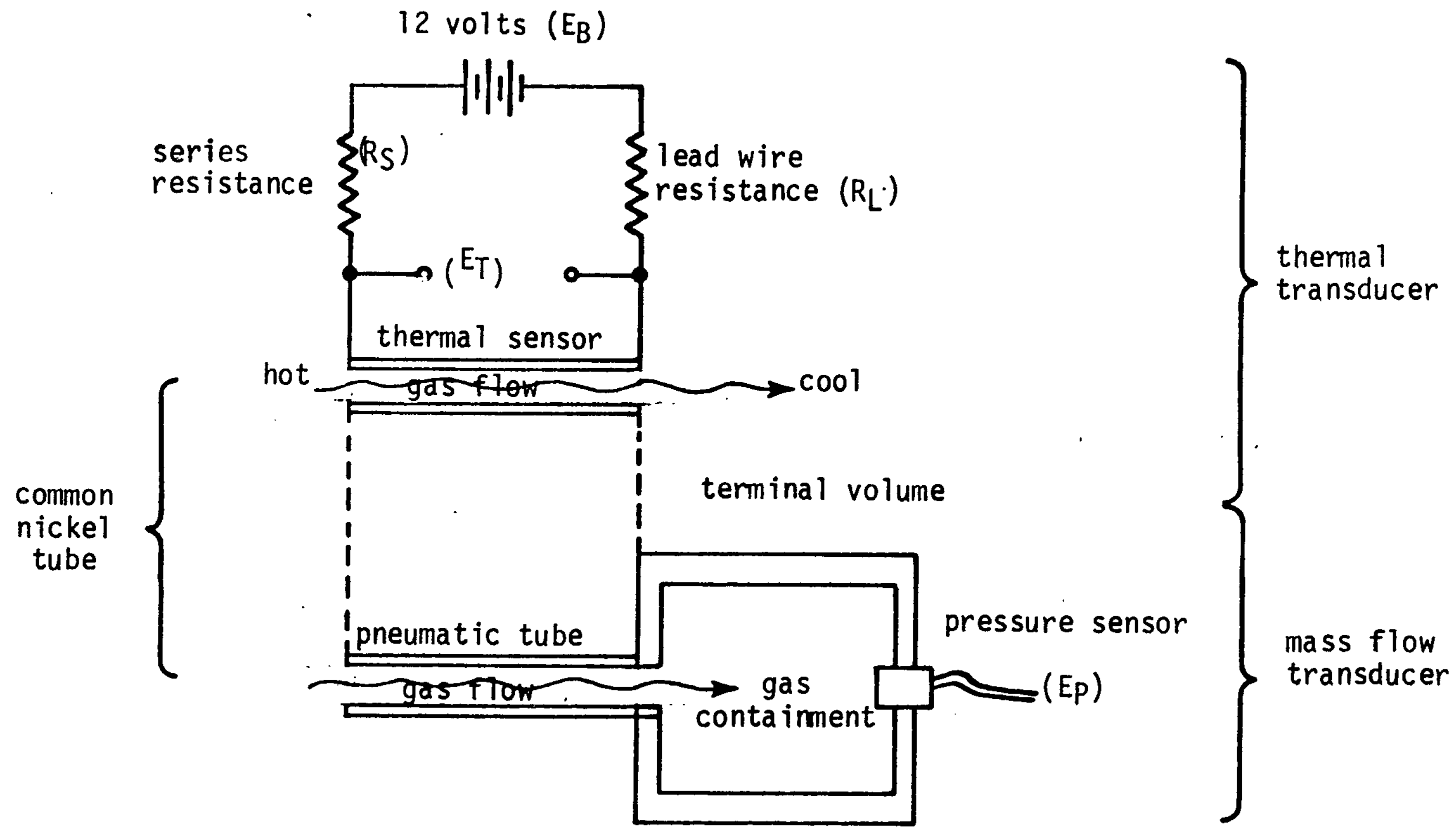

FIGURE 2. COMMON THERMAL AND PNEUMATIC TUBE

2. <u>Probe Configuration</u> - Figure 3 is a picture of the probe. It is more massive than previous Calspan designs [6,7] to provide for structural strength needed for exposure to flow typical of RENT:

Mechanical loads to 11g

Mach Number - 1.2 to 2.5

Enthalpy - 7150 BTU/LBM

Stagnation pressure to 100 atmospheres

A change in configuration, as shown in Figure 4, was necessitated to adapt the probe to model strut number 4 (see Figure 5) of the RENT.

a. Thermal Transducer - Energy is absorbed by a 6" nickel tube sensor placed in one arm of a half-bridge. The rate of energy absorbed is proportional to the rate at which the electrical resistance of the tube increases. It is assumed that the radiant loss rate which is a function of the instantaneous resistance, and conduction losses to the tube end supports are negligible. Further, it is assumed that changes in the energy content of the gas before it reaches the thermal sensor and energy input due to stagnation heating on the cap are negligible. Thus the differential electrical output of the thermal transducer is assumed to be in the direct proportion to the energy contained within a unit mass of the gas before it enters the probe. For steady flow conditions, the time to reach 96% of steady flow is

$t = 4L/Va$ (see Reference 8) (2)

by considering a cold flow situation and the tube to be a long nozzle throat having no pressure loss. Va, (the acoustic velocity of air) =1100 ft/sec and L = tube length in inches. For the 6" tube of the subject probe the time to 96% of steady flow is 1.8 milliseconds. It follows then that an equal amount of time is required for the energy contained in a given amount

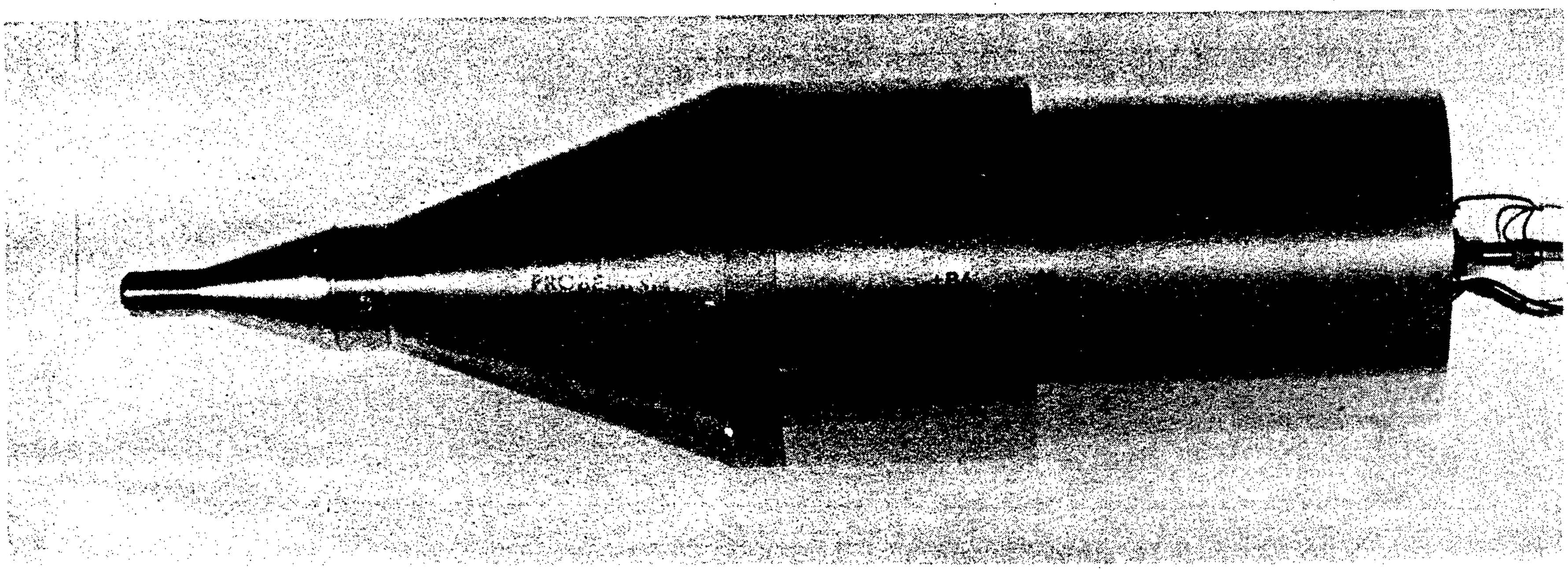

FIGURE 3. CALSPAN PROBE

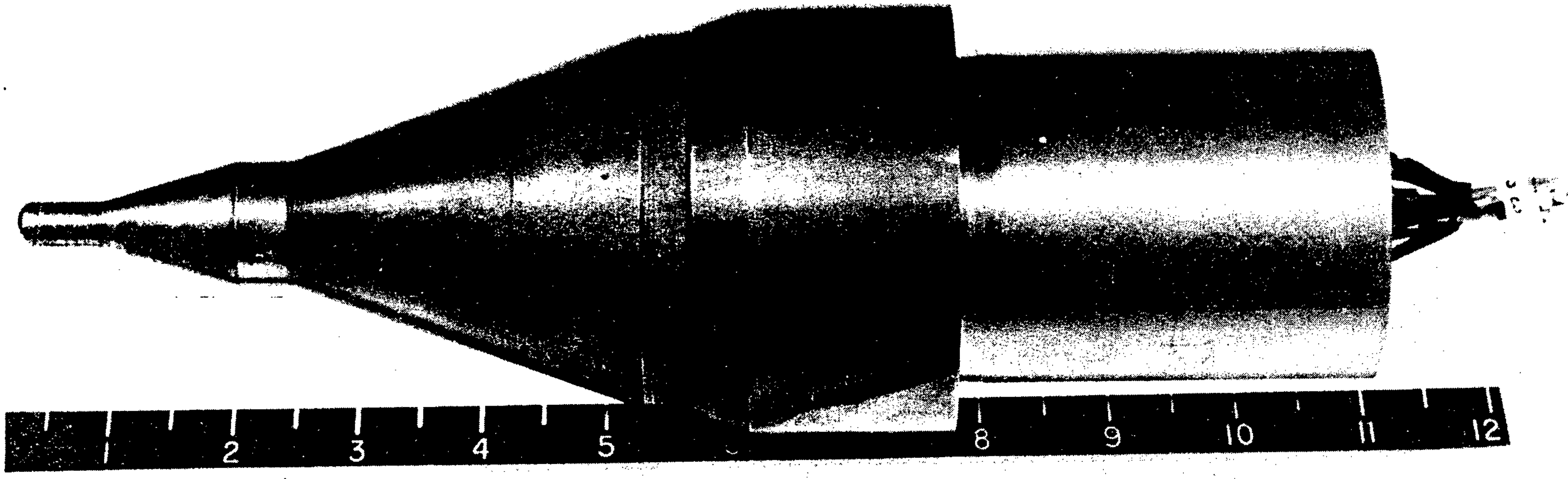

FIGURE 4. RENT CONFIGURATION OF CALSPAN PROBE.

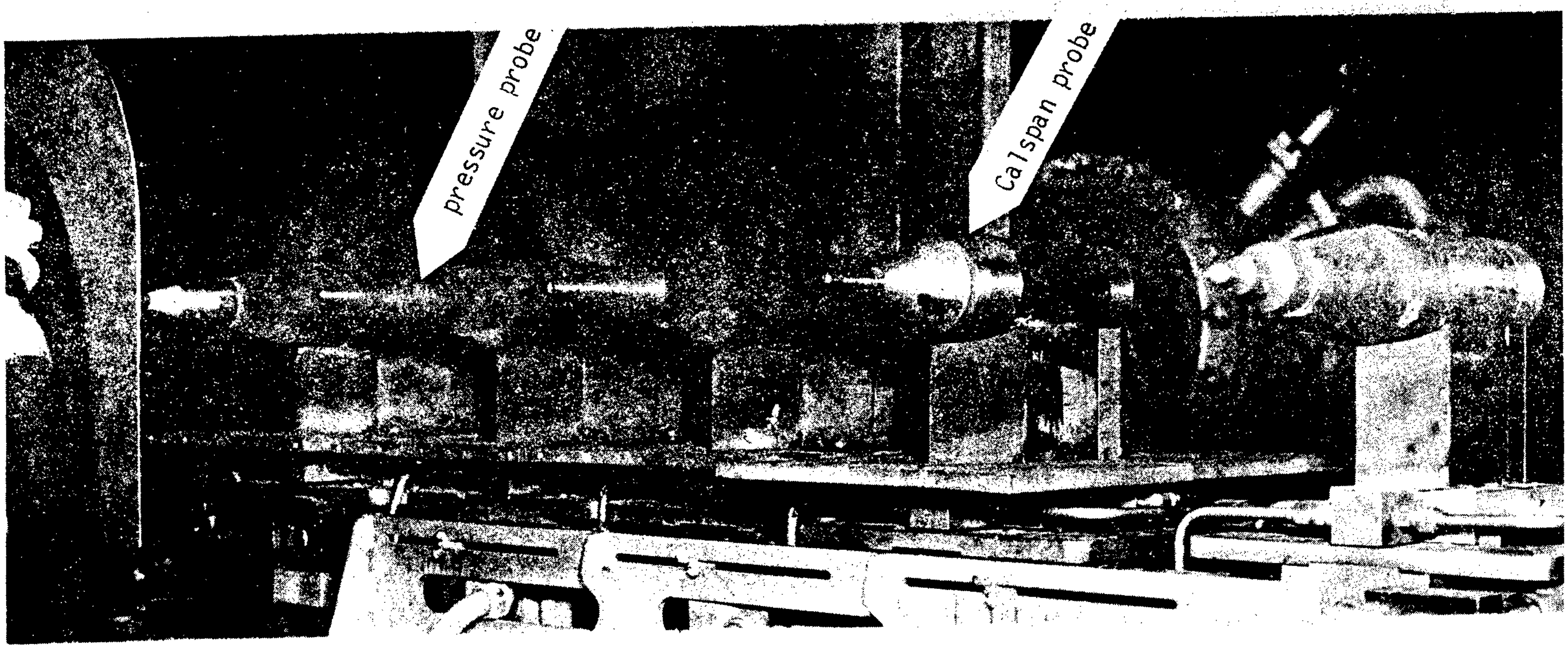

FIGURE 5. PROBE ON RENT MODEL CARRIAGE STRUT NO. 4.

of gas to be transferred to the tube, since steady conditions would not be attained until the rate of change of heat transfer from the gas became constant.

b. Mass Flow Transducer - The nickel tube of this transducer is common with the thermal transducer. The mass flow transducer sensor is a PCB Piezotronics, Inc., model number 102A12, quartz crystal circuit. It has the following manufacturer's specifications:

Sensitivity = 20 $\pm$ 4mV/psia

Resolution = .01 psia

Resonant Frequency = 500,000 Hz

Rise Time = 1 microsecond

Linearity = 1% of full scale

Range 10V output for 500 psia   Max Pressure = 1000 psia

The response of the mass flow transducer is not the same as the pressure sensor specifications because of the length of the pneumatic tube and volume elements upstream of the pressure sensor. The minimum delay is the time required for sound to travel the length of the volume plus time required to reach steady flow in the tube. The volume length is 4.75". Therefore, 3.6×10^{-4}s are required for a velocity of sound in air of 1100 ft/s. Adding this to the 1.8 milliseconds estimate for steady flow to be established in the tube gives 2.16×10^{-3}s, the minimum time in which the two probe outputs are indicative of enthalpy as defined in the concept.

TYPICAL TEST DATA

Table I is the Calspan probe data for RTN 33-060. A valid analysis of this data depends on determining the initial interval at which at least 2.16 milliseconds of unchanging RENT flow conditions exist across the diameter of the flow. This determination was made by examining the data from the pressure probe on strut number 2. This data is in Table II.

TABLE I

CALSPAN PROBE DATA

RTN 33-060

TEST TIME	COMPUTER VOLTS		PROBE DISTANCE FROM NOZZLE CENTER (INCHES)
MILLISECONDS	ΔE_T X10^2	E_P X 10^2	
87	.115	.911	-.655
88	.134	.959	-.608
89	.168	1.027	-.561
90	.319	1.110	-.519
91	.544	1.262	-.468
92	.789	1.408	-.421
93	1.027	1.564	-.375
94	1.271	1.696	-.327
95	1.525	1.838	-.283
96	1.789	1.970	-.234
97	2.028	2.087	-.190
98	2.268	2.229	-.145
99	2.507	2.336	-.096
100	2.770	2.438	-.056
101	3.034	2.575	-.002
102	3.303	2.717	.043
103	3.571	2.810	.092
104	3.835	2.941	.137
105	4.113	3.044	.188
106	4.411	3.156	.232
107	4.704	3.269	.279
108	5.041	3.366	.324
109	5.388	3.479	.373
110	5.666	3.576	.418
111	5.964	3.674	.466
112	6.198	3.767	.512
113	6.335	3.801	.558
114	6.384	3.737	.604
115	6.384	3.708	.649

TABLE II

PRESSURE PROBE DATA

RTN 33-060

TEST TIME MILLISECONDS	RADIAL POSITION OF PROBE (INCHES)	VOLTS (PRESSURE)
146	-.534	.046
147	-.504	.232
148	-.472	.552
149	-.443	1.325
150	-.417	2.302
151	-.381	3.483
152	-.35	4.470
153	-.32	5.119
154	-.289	5.510
155	-.259	5.739
156	-.229	5.935
157	-.200	6.052
158	-.170	6.150
159	-.138	6.198
160	-.108	6.218
161	-.077	6.198
162	-.056	6.091
163	-.012	6.228
164	.016	6.218
165	.0463	6.286
166	.0783	6.247
167	.1086	6.325
168	.139	6.355
169	.169	6.282
170	.203	6.326
171	.230	6.369
172	.262	6.247
173	.292	6.189
174	.323	6.291
175	.353	6.062
176	.383	6.018

DATA ANALYSIS

Examination of test data shows the pressure probe time response is longer than the 2.16 milliseconds response of the Calspan probe. Therefore, it is concluded that the Calspan probe is exposed to a nearly constant enthalpy level at least over the distances that the pressure probe indicates a nearly unchanging profile. This distance can be estimated for Table II over the time that the pressure probe voltage is essentially constant. This is the case for about 16 milliseconds after the test time of 159 milliseconds. Since the probe output lags the actual input, the constant level pressure was encountered earlier than the 159 milliseconds time. It is governed by a single dominant capacitive energy storing element in estimating the lag time. Although the initial portion of the flow profile must contain gradients in the region of the nozzle edge, the pressure curve can be considered as having been caused by a step increase in pressure. The time that this step occurs is calculated to be at 149.34 milliseconds using the analysis in Reference 9. In terms of distance, the constant pressure level occurs at -.426 inch from the nozzle centerline. This result is assumed to apply even though a sharp step is not evident in the data.

Thereby it is concluded that since the pressure probe on strut number 2 encountered a pressure profile which consisted predominately of a step increase to the maximum pressure at -.426 inch from the flow centerline, the Calspan probe on strut number 4 encountered the same step increase at -.426 inch also. Referring to Table 1, it is shown that the Calspan probe reached -.426 inch between 92 and 93 milliseconds. Adding 2.16 milliseconds gives the start of valid Calspan probe data between 94.16 and 95.16 milliseconds.

The start was set at 95 milliseconds for analysis to gain the simplicity of using the actual rather than fractional deviations from the recorded data.

Equation 1 is thereby valid after computer time of 95 milliseconds for RTN 33-060 and is interpreted as follows:

$$Hg = \frac{277{,}000}{E_T \times 10^3} \; \frac{\Delta E_t/\Delta t}{Ep/\Delta t} \; \frac{Gp}{GT} + 155 \text{ BTU/LBM} \qquad (3)$$

where Δt = 1 millisecond time intervals after 3 milliseconds of probe exposure to an unchanging flow condition. Gp and GT = gains produced at ΔEp and ΔE_t during signal conditioning. If the flow conditions are assumed to be changing, then the time interval, Δt, must be long enough to cover the period required for the probe to fully respond to the change. This value is 2.16 milliseconds after the time that change starts. In the RENT tests the beginning of a change can only be detected in the computer recorded data with a certainty of 1 millisecond. Additionally, if the number of changes is more than one per 2.16 milliseconds + (1 ms) then full response of the probe is never certain within this 3 millisecond interval and the data can't be used in equation 3. Three successive data points at least 2.16 milliseconds apart, which have the same slope between them is the minimum indication of valid data. It follows that data points only 1 millisecond apart which follow three such points as defined above are also valid. In general then, if it is known that the flow being measured has an enthalpy profile of constant slope, then all data recorded after an exposure of 2.16 milliseconds can be assumed to be valid. Otherwise, a test like the one mentioned must be performed to define valid data points.

In Figure 6, detailed enthalpy probe data and the results, (Hg-155) using Equation 3, and Δt = 1 ms are plotted along with the pressure probe data. The (Hg - 155) plot is extended beyond the times of probe position in front of the nozzle, including positions on each side of it. Though the $\Delta E_T/E_p$ curves appear smooth, the (Hg - 155) curve calculated from the ratio $\Delta E_T/E_p$ show gross deviations, even over the extended regions. According to the previously mentioned test for valid data, deviations should be expected between the first two or three points after - .426 inches only. The (Hg - 155) deviations can be attributed to two reasons. One, the error range of the recording, or electrical noise peculiar to data conditioning or in the signal generation and transmission circuits. The change in E_T and E_p over one millisecond is in the range of .1 to .3 computer volts, where the range of computer volts is 10. Therefore these values represent a change 1 to 3% of range. If recording occurs with an uncertainty of only ± .25% of this range, the uncertainty in the calculated values of (Hg - 155) can be very large. For example, if

$$E_T \text{ @ } 96 \text{ ms} = 1.789 \pm .025\text{V}$$

$$\text{AND } E_T \text{ @ } 97 \text{ ms} = 1.525 \pm .025\text{V}$$

then the range of ΔE_T including uncertainty is .214 to .314V. For Ep at these times, the possible values are 1.970 ± .025 Volts and 1.838 ± .025 Volts. The range of the $\Delta E_T/\Delta E_p$ ratio

$$\frac{(1.789 - 1.525) \pm .05\text{V}}{(1.970 - 1.838) \pm .05\text{V}}$$

has a maximum value of 3.83 and a minimum value of 1.18. The ratio calculated with an uncertainty of zero is 2.0. Therefore the value of (Hg-155) calculated over the 95 to 96 ms interval could have a factor of uncertainty ranging from .587 to 1.9 of the ratio calculated with an uncertainty of zero.

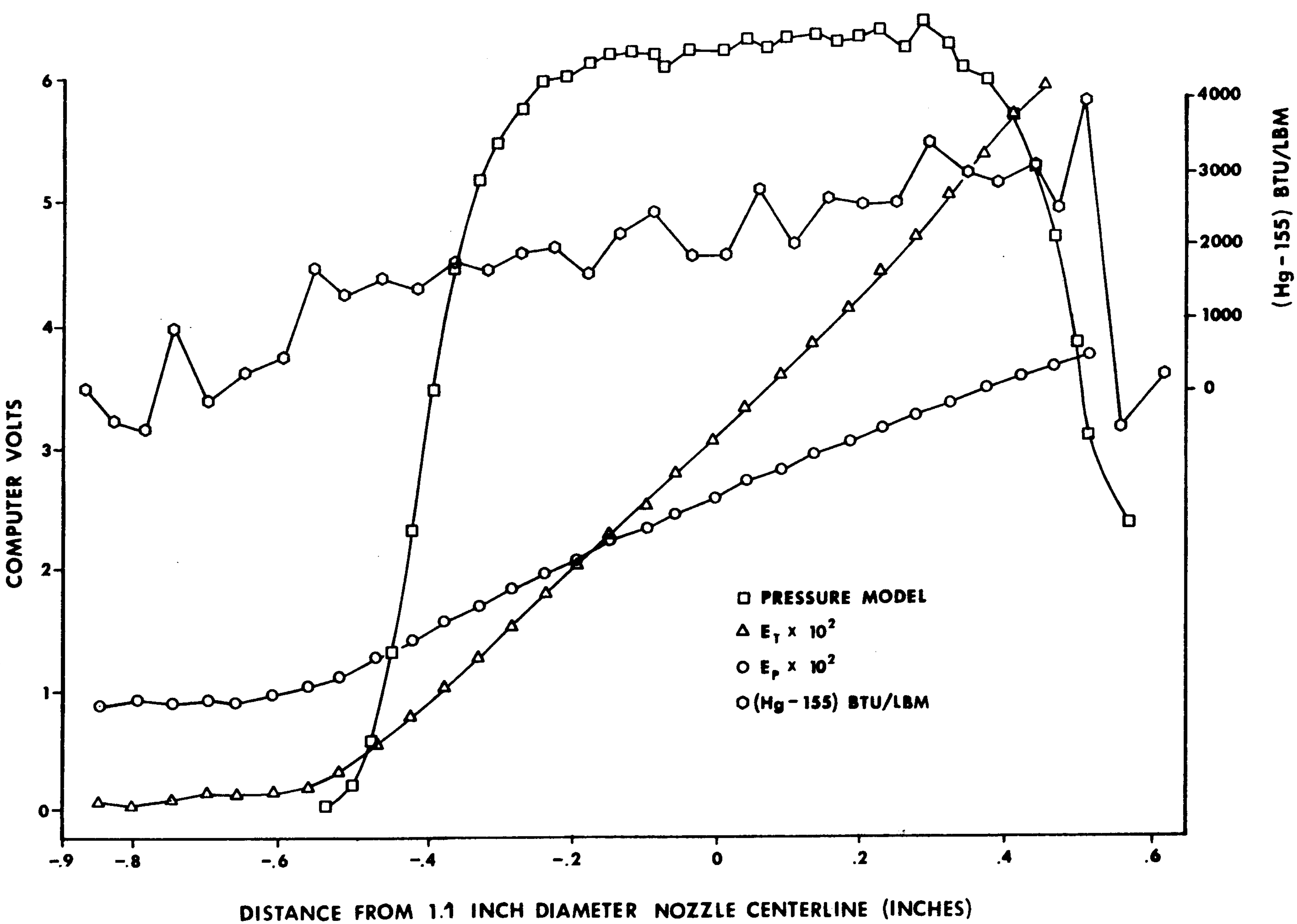

FIGURE 6. Plotted Data and Results for 1 ms Intervals

Table III gives the values of Hg by adding 155 BTU/LBM to the data plotted in Figure 6. As discussed above, the variations in Hg are probably indicative of electrical noise.

To obtain an estimate of the average enthalpy, lines were drawn between the 95 and 106 ms points to determine a single value for $\Delta E_T/\Delta t$ and $\Delta E_P/\Delta t$. These are the longest possible lines. Further extensions deviate increasingly from both the E_T and E_P curve. Referring to Table I for the voltages at these points, and calculating the slopes, results in

$$\frac{\Delta ET}{\Delta t} = 262.4 \quad V/s \tag{4}$$

$$\frac{\Delta ET}{\Delta t} = 119.8 \quad V/s \tag{5}$$

Then substituting into equation (3) where $G_P = G_T = 100$, and $E_T = 294 \times 10^{-3}$ volts gives (6)

$$Hg = [\frac{277,000}{294} \left(\frac{262.4}{119.8}\right)\frac{100}{100} + 155] \text{ BTU/LBM}$$

$$Hg = 2218 \text{ BTU/LBM} \tag{7}$$

In a similar fashion the results of RTN 33-058, 059, 061, and 062 were derived yielding these values:

Test No.	058	059	060	061	062
Hg, BTU/LBM	2286	2192	2218	2273	2246

TABLE III

Hg For Δt = 1 ms

DISTANCE PROBE NOZZLE CENTER DURING SWEEP FROM - TO +	Hg OVER 1 ms INTERVALS
-.655	-
-.608	528
-.561	626
-.519	1869
-.468	1550
-.421	1736
-.375	1592
-.327	1897
-.283	1840
-.234	2039
-.190	2080
-.145	1747
-.096	2259
-.056	2584
-.002	1971
.043	1940
.092	2870
.137	2054
.188	2698
.232	2662
.279	2598
.324	3428
.373	3048
.418	2855
.466	3019
.512	2526
.558	3950
.604	-566
.649	155

VALIDITY OF THE MEASUREMENT TECHNIQUE

Vassallo plotted the ratio of the probe outputs $\Delta E_T/\Delta E_p$ versus the enthalpy of a 2910°F gas at pressures up to 21 atmospheres. The slope of the data is essentially constant. It appeared therefore that the calibration constant and equation would be valid for RENT, a different facility from that in which the constant was established.

A comparison of the average enthalpy calculated with RENT bulk enthalpy, Table IV, appears to verify that the linearity of the calibration holds, if an assumption that bulk enthalpy is approximately 20% less than the free stream enthalpy value is valid. But the calculated values of enthalpy are questionable otherwise because of thermal and electrical effects on the thermal sensor which are not taken into account in the probe equation used for this test. These effects are more significant in RENT, than in the 2910°F calibration medium.

a. In Equation (2), $\Delta E_T/E_T$ is assumed to be equal to $\Delta R_T/R_T$ as explained in Reference 5, but a complete solution for $\Delta E_T/E_T$ associated with the half bridge gives

$$\frac{\Delta R_T}{R_T} = \frac{\Delta E_T}{E_T}\left[1 + \frac{R_T + \Delta R_T}{R_L + R_S}\right] \qquad (8)$$

For the values in the circuit used

$$\frac{R_T + \Delta R_T}{R_L + R_S} = \frac{8.708 \times 10^{-2} + \Delta R_T}{3} \qquad (9)$$

Therefore the probe equation has an initial error of approximately -2.9% which increases as ΔR_T increases. For example, at a change in average tube temperature of 200°F, an error of approximately -10% results for a temperature coefficient of resistance of the tube of .01226 ohms per ohm per °F.[10]

b. The constant 277,000 BTU-Volts/LBM contains the ratio of the specific heat of nickel to the temperature coefficient of resistance. This ratio varies with temperature significantly, but the constant used in the equation is considered non-varying.

c. The thermal interchange between the aspirated gas and the internal surface of the copper cap is not defined.

d. The conduction heat load to the tube as a result of stagnation heating of the cap is not defined.

These effects disallow a conclusion that valid measurements in RENT were made.

TABLE IV

BULK ENTHALPY AND CALSPAN AVERAGES

TEST NO.	058	059	060	061	062
Bulk Enthalpy (BTU/LBM)	1910	1800	1950	1920	1800
Table III Data (BTU/LBM)	2286	2192	2218	2273	2246

CONCLUSIONS

The swept measurements obtained in RENT during sweeps where no peak in the enthalpy profile was expected, give significant information about the Calspan probe performance. At sweep speeds over the range 50 to 80 inches per second, the probe survived the flow very well. Total test times were short with respect to the 2.16 ms time response of the mass flow transducer. This is the dominating response time of the probe. Therefore, only the data obtained 2.16 milliseconds after exposure to the maximum and unchanging average enthalpy was considered valid. This data showed unexpected fluxuations and an increasing trend when a point by point analysis was used. The results based on average slope measurements were more characteristic of previous Calspan results. The increasing trend was still evident. The cause of these fluxuations and the increase was not resolved, but could be due to electrical noise, thermal losses, disparities between the concept and the hardware configuration, or actual fluxuations in the RENT flow.

Expansion of the equation to include the known thermal and electrical effects not now included would improve the data quality. Additional signal conditioning of the probe transducers to match the time response of each and provide for a single output signal would produce a more valid instrument. Improvements in configuration along with these modifications could shorten the time response.

Though the probe configuration can be improved for RENT, a configuration for instantaneous measurements of a highly fluxuating flow seems impractical because of the lower frequency limitations of physical systems. However, more accurate measurements of the average enthalpy for flat profile conditions is practical.

REFERENCES

1. Huber, F. J., Probes for Measuring Mass Flux, Stagnation Point Heating, and Total Enthalpy of High Temperature Hypersonic Gas Flows, AIAA Paper No. 66-750, AIAA Testing Conference, Sep 21-23, 1966.

2. O-Conner, T. J. et. al., Enthalpy - Mass Flux - Impact Pressure Probe System, AFFDL-TR-68-137, Dec 1968.

3. Pigott, J. C., Development of Calibration Instrumentation for Ablation Facilities, Sep 1971, AEDC-TR-71-172.

4. Conley, Hudson L., Enthalpy Measurements in the RENT Facility Using the AEDC Transient Enthalpy Probe, AFFDL-TM-74-124-FXN, May 1974.

5. Vassallo, F. A., Rapid Response Enthalpy Probe Development, ARL 73-0183, Dec 1973.

6. Vassallo, F. A., High Speed Miniature Enthalpy Probe Development, ARL 70-0018, Feb 1970.

7. Vassallo, F. A., Miniature Probes for the Instantaneous Measurement of Enthalpy in Arc Jets, ARL 67-0181, Sep 1967.

8. Vassallo, F. A., Miniature Enthalpy Probes for High Temperature Gas Streams, ARL 66-0115, June 1966.

9. Stein, P. K., Measurement Engineering, Vol I, Chap 4, Stein Engineering Serivces, Inc., 1964.

10. Norton, H. N., Handbook of Transducers for Electronic Measuring Systems, Prentice-Hall, Inc., 1969, p. 587.